

Geoenvironmental Assessment of Heavy Metal Contamination in Industrially Impacted Soil Using Pollution Indices

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doi.org/10.64643/IJIRTV12I10-204357-459

Abstract—Industrial actions may radically alter quality of soil through the accumulation of heavy metals, creating hazards to the environment and human health. This study evaluated heavy metal contamination in soils collected from an industrially contaminated site with the help of pollution indices. Surface soil samples were collected at six locations within the site (S1-S6), and one sample was taken to represent the background or control sample condition. Lead, zinc, cadmium, chromium, iron, and manganese were analysed. The degree of contamination was determined using the Contamination Factor (CF), Geo-accumulation Index (I_{geo}), and Pollution Load Index (PLI) methods, based on the background sample reference. Most metal concentrations were high in contaminated soils compared with the control soil. Soil contamination by lead and zinc was moderate to high in some locations, while iron and chromium were extremely increased. Cadmium was detected only at two locations and was below the detection limit in the other four samples. The findings indicate that contamination was unevenly distributed across the site, sampling location S5 showing the highest pollution, S4 and S6 also shows notable degree of contamination. The overall observations disclosed that the study area is affected by industrial heavy metal and requires continuous monitoring and site-specific management interventions to resolve environmental risk.

Index Terms—Contamination Factor, Geo-Accumulation Index, Geo-Environmental, Heavy Metals, Pollution Load Index, Soil Contamination

I. INTRODUCTION

Soil is a living reserve that supplies essential moisture and nutrition to vegetation, and also maintaining the balance of the ecosystem. Soil is extremely vulnerable to disruption when contaminated by harmful

substances that alter its natural properties. The introduction of such toxic substances into the environment may alter natural processes and can create ecological imbalance and health risks, and described as pollution. Different forms of environmental pollution are air, water, and soil pollution, and these are interconnected. Soil pollution is a priority issue nowadays, because it poses a direct threat to agricultural productivity, water quality, and environmental balance (Cachada et al., 2018; Iberdrola, 2021; Münzel et al., 2023).

Industrial growth has made this problem sharper. Soil contamination has heightened through the gradational accumulation of heavy metals. Unlike many other organic pollutants, heavy metals do not break down over time. Their gradual accumulation may reach levels that adversely affect environmental quality and human health over long time (Che Lat et al. 2023).

Anthropogenic Activities, like industrial emissions, waste disposal, vehicular inputs, ore processing, electroplating, are associated with heavy metal contamination. Metals such as lead, cadmium, chromium, and zinc are especially concerning because their toxicity, persistence, and ability to enter the food chain. Even elements such as iron and manganese may become critical contaminants when their concentrations increase beyond background level. (Demirtepe 2024)

The assessment based solely on total metal concentration is often insufficient to adequately explain the magnitude of soil contamination. Therefore, pollution indices are predominantly used in environmental studies to juxtapose observed metal concentrations against background levels and to categorize the degree of contamination (Ferreira et al.

2022). Among the most frequently used indices are the Contamination Factor (CF), Geo-accumulation Index (I_{geo}), and Pollution Load Index (PLI), which provide a practical framework for appraising pollution intensity and identifying contamination hotspots. (Mandal, Bhattacharya, and Paul 2022)

This study aimed to examine heavy metal contamination in soils from an industrially polluted region of Kerala. Concentrations of Pb, Zn, Cd, Cr, Fe, and Mn determined from six sampling sites together with a control site served as the basis for evaluation. The main objectives were to investigate the distribution of these metals in the study area, assess contamination levels using the Contamination Factor (CF) and Geo-accumulation Index (I_{geo}), and evaluate the overall pollution status of the site using the Pollution Load Index (PLI).

II. MATERIALS AND METHODS

2.1. Study area

The investigation area selected for this study is in of Kerala which has been suffering from prolonged periods of industrial pollution. Under such circumstances, it may be noted that the process of contamination does not result from a single point of origin. Rather, it results from a gradual process of contamination that results through various means, such as the functioning of factories, waste disposal, atmospheric contamination, and other by-products of continued growth of industries. The surface soil, in this regard, seems to be subject to considerable contamination. They do not simply support vegetation or construction. They also function, somewhat uneasily, as long-term receivers of pollutants, including heavy metals. For that reason, the area was considered appropriate for examining how far heavy metal contamination had developed in the local soil environment.

To capture how contamination might vary across the site, samples were collected from several locations likely to be influenced by nearby industrial activity. The logic here was fairly straightforward, though not simplistic. Pollution is rarely spread evenly across land, even within the same industrial zone. A point closer to a waste discharge area, for example, may show a very different metal profile from one exposed mainly to airborne deposition. Alongside these impacted locations, a control site was selected from a

relatively less disturbed area to provide a background reference. That sample was used to compare metal concentrations and to calculate the pollution indices applied in the study. More fundamentally, it enables the distinction to be made between elements that are part of the inherent geochemical signature of the soil and those that are part of any industrial contamination. It is true that, even at a control site, there will be no such thing as a totally pristine environment in a densely utilized landscape; however, it is an essential baseline for interpreting levels of contamination.

2.2. Soil sampling

Soil samples were collected at six points within the industrially affected zone. These points were designated S1 to S6. Additionally, one point was designated at the control site. The points were chosen to ensure that diverse parts of the affected area were included. This is a significant consideration in light of the fact that pollution in industrially affected environments is usually irregular and unpredictable. This is because a point near an effluent pathway may have characteristics that differ significantly from points near pathways such as dust or surface runoffs. At each location, surface soil was collected using standard field procedures. Prior to sampling, the topmost layer of the soil, consisting of the litter layer, plant residues, and other extraneous materials is carefully removed to obtain more accurate representations of the actual surface horizon of the soil that is exposed. The soil samples were collected, properly labelled, and stored in containers to avoid the possibility of cross-contamination of the soil samples. Upon receipt of the collected soil samples at the laboratory, they were subjected to air-drying at room temperature. During the process of drying the soil samples, impurities such as roots, stones, and other large debris were manually separated from the soil samples. The dried samples were then processed further for heavy metal analysis.

2.3. Heavy metal analysis

The soil samples collected were tested to determine the quantities of certain heavy metals present in the soil. The metals considered for this study were lead (Pb), zinc (Zn), cadmium (Cd), chromium (Cr), iron (Fe), and manganese (Mn). Out of these heavy metals, Pb, Cd, and Cr are most commonly known for their toxic nature. On the other hand, iron and manganese

are natural substances that may become hazardous at higher concentrations.

2.4. Pollution indices

In order to assess the soil contamination more effectively, the study made use of not only the measured metal concentration values, but it also took into consideration a number of pollution indices. While it is true that measured values of metal contamination are significant, it is also true that such values are not adequate to give an accurate picture of the extent of contamination. This is because any given measured value may be either high or low, without any clear indication of whether it is a result of natural processes or human influence. Pollution indices help to address this issue by comparing the measured values to the background values. They are also helpful in determining the portions of the study area where contamination may be more severe.

In this study, three commonly used indices have been employed. These are Contamination Factor (CF), Geo-accumulation Index (I_{geo}), and Pollution Load Index (PLI). Each of these indices has a different point to make on the same subject. The Contamination Factor gives a metal-specific evaluation, the Geo-accumulation Index allows evaluation on the degree of accumulation, and the Pollution Load Index gives a wider evaluation on the subject. All these indices, taken together, provide both element-specific as well as site-specific evaluation. Though these indices have been criticized, they are still useful tools for understanding the subject. The evaluation of these indices is still largely contingent on the reliability of background values.

2.4.1 Contamination Factor (CF)

The Contamination Factor (CF) was used to measure the level of contamination of a given heavy metal with respect to its background concentration. It was calculated as a ratio of concentration in the sample to that in the control sample. This measure gives a direct reading of the level to which a heavy metal is contaminated in a given area with respect to its background concentration.

$CF = C_s / C_b$, where C_s represents the concentration of the metal in the soil sample and C_b represents the concentration of the same metal in the control sample (Ahmed et al. 2023).

The Contamination Factor (CF) values were interpreted based on the usual classifications that are used in studying contaminations. A CF value less than 1 indicates low levels of contamination, which means that the concentration of metal is at or close to background. A CF value that ranges from 1 to 3 indicates moderate levels of contamination, while a value that ranges from 3 to 6 indicates considerable levels of contamination. A value greater than 6 indicates very high levels of contamination.

The above classification will be useful for determining which metals show the highest level of enrichment at any sampling location. In this respect, CF will be a relatively straightforward tool. It does not take into consideration all metal properties in soils, but it will give a rapid impression of where the levels of contamination are low or where they are higher.

2.4.2 Geo-accumulation Index (I_{geo})

The Geo-accumulation Index (I_{geo}) has been used to measure the extent of accumulation in the soil, and to determine the influence of anthropogenic activities on the concentration of metals. The Geo-accumulation Index compares the measured concentration with the background concentration, taking into account a correction factor to account for any changes in the environment.

$I_{geo} = \log^2 [C_n / (1.5B_n)]$, where C_n is the measured concentration of the metal in the soil sample and B_n is the corresponding background concentration in the control sample. The constant 1.5 is included to minimize the effect of natural fluctuations in background values due to lithological or minor environmental variations.

The I_{geo} scale is widely used to classify contamination into different categories, ranging from unpolluted to extremely polluted. Negative or near-zero values generally indicate unpolluted conditions, whereas increasing positive values suggest greater metal accumulation and stronger anthropogenic influence. In the present study, I_{geo} was applied to better understand the contamination level of each metal and to complement the results obtained from the Contamination Factor.

2.4.3 Pollution Load Index (PLI)

Pollution Load Index (PLI) has been used to measure the overall level of pollution at each point of sampling by taking into consideration the contamination factors

of the metals analysed. Unlike the Contamination Factor (CF) and Geo-accumulation Index (I_{geo}), which focus on individual metals, the Pollution Load Index (PLI) allows for an integrated assessment of the total level of contamination at any point of sampling. Such a feature makes the Pollution Load Index (PLI) suitable for making comparisons between different points of sampling.

$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{(1/n)}$, where CF_1 , CF_2 , CF_3 , CF_n are the contamination factors of the individual metals and n is the total number of metals included in the calculation.

A Pollution Load Index (PLI) less than 1 implies no pollution or a baseline condition. Similarly, a PLI equal to 1 represents the reference level of pollution. Any value greater than 1 implies a worsening in the quality of the soil. This also represents the presence of pollution. In this present research, the PLI was used to locate the worst affected sampling points and to present a general overview of the level of contamination in the industrially affected area.

III. RESULTS AND DISCUSSION

3.1. Heavy metal concentrations in soil samples

Table 1. Heavy metal concentrations in soil samples

Metal Concentration (mg/kg)	S1	S2	S3	S4	S5	S6	Control
Lead (Pb)	39	36	98	54	41	48	28
Zinc (Zn)	107	45	49	78	88	64	35
Cadmium (Cd)	BDL	BDL	0.5	0.5	BDL	BDL	BDL
Chromium (Cr)	274	259	282	326	398	268	118
Iron (Fe)	28784	28991	27240	37320	51435	42171	2051
Manganese (Mn)	163	208	269	275	521	182	128

The concentration values showed spatial variations at the sampling points. This suggests that there are differential impacts of industrial activity within the study area. The values of lead in the impacted samples ranged from 36 to 98. The maximum value of lead occurred at S3. Zinc values ranged from 45 to 107. The maximum value of zinc occurred at S1. Cadmium values were below the detection limit at most of the sampling points. It was detectable at S3 and S4, each having a value of 0.5.

The concentration of chromium was consistently higher in all the affected samples compared to the control. The values of chromium were ranging from 259 at S2 to 398 at S5. The highest concentration of iron was recorded in all the metals under study. The iron concentration varied from 27,240 at S3 to 51,435 at S5, with the control recording 2,051. The concentration of manganese varied from 163 to 521. The highest value of manganese was recorded at S5. The above values indicate that the sampling location S5 is the most affected.

In general, the increased Pb, Zn, Cr, Fe, and Mn concentrations in relation to the control sample indicate that there is a significant impact of industrial activity on soil quality. The spatial variations of metal concentration also show that the distribution of

contaminants is not random; it is affected by local conditions such as waste distribution, surface runoff, precipitation, and proximity to pollution sources.

3.2. Contamination Factor (CF)

Table 2. Approximate contamination factor (CF) values

Met al	S1	S2	S3	S4	S5	S6
Pb	1.39	1.29	3.50	1.93	1.46	1.71
Zn	3.06	1.29	1.40	2.23	2.51	1.83
Cr	2.32	2.19	2.39	2.76	3.37	2.27
Fe	14.03	14.13	13.28	18.20	25.08	20.56
Mn	1.27	1.63	2.10	2.15	4.07	1.42

The values of the contamination factor clearly indicate that the degree of metal enrichment varies from metals to metals as well as from location to location. Iron had the highest CF values at all locations, remaining within the 'very high contamination' category. This is an

indication of a large anthropogenic contribution to iron enrichment, implying that there is continuous industrial activity in the area.

Chromium showed a moderate level of contamination at most sites, but a considerable level of contamination at S5. Zinc also showed a considerable level of contamination at S1, but the other sites showed a moderate level of contamination. Lead showed a moderate level of contamination at most sites, but a considerable level of contamination at S3, which indicates a localized zone of high Pb accumulation. Manganese showed a moderate level of contamination at most sites, but a considerably high level of contamination at S5.

Overall, the results from the CF analysis suggest that Fe is the most important contaminant in the study area, with Cr, Zn, Pb, and Mn being secondary contaminants. The fact that S5 is again identified as a location with high CF values may indicate that this point is closer to a major contaminant source, or perhaps it is acting as a "deposition point" where contaminants accumulate.

3.3. Geo-accumulation Index (I_{geo})

The Geo-accumulation Index also offered further insight into the pattern of contamination by comparing the levels of metals present with the background levels. The results from the I_{geo} also confirmed the pattern already seen in the CF values. Iron was seen to have the highest level of accumulation in all the sampling points. This confirmed that the concentration was way above the expected background level.

Chromium, in most cases, fell in the range of the lower to moderate contamination classes, which implies that though the enrichment of Cr is substantial, it is not as extreme as that of Fe. The contamination classes of lead and zinc were mainly in the range of low to moderate, which again implies anthropogenic influence, though to a lesser extent than in the case of Fe. Manganese, in most cases, fell in the range of the lower classes of contamination, with the exception of site S5, where the higher concentration reflected a higher accumulation.

Cadmium could not be assessed in a meaningful way using I_{geo} , as it was below the detection limit in most of the samples and also not detected in the control. In such a case, the index value may not be reliable, and a different approach has to be employed in dealing with the problem. The detection of Cd at S3 and S4,

however, needs special consideration, as cadmium is a toxic metal even at low concentrations.

3.4. Pollution Load Index (PLI) and overall site condition

The Pollution Load Index was used to represent the cumulative effect of all the analysed metals at each sampling point. This index provided an integrated view of the cumulative effect of all the metals, unlike the CF and I_{geo} values, which give an individual view of each metal. Based on the calculated values, all the locations have values of the Pollution Load Index greater than 1, showing that the soils are polluted.

Among these sampling points, S5 had the highest overall pollution burden, followed by S4 and S6. This is in fairly good agreement with the metal concentration and CF results, where S5 is again ranked as the most polluted location. The overall ranking of the severity of pollution may be summarized as follows: $S5 > S4 > S6 > S1 > S3 > S2$. This ranking indicates that the severity of contamination decreases as we move away from the more impacted zones; however, even the least impacted of these sampling points still has some level of pollution above baseline conditions.

The findings based on the concentration data and pollution indices collectively affirm that the area under investigation has been affected by human industrial activities. Areas with high levels of pollution can be related to waste disposal practices, pathways of industrial particulate matter in the atmosphere, pathways of runoffs, and the accumulation of metals in the soil.

3.5. Discussion of environmental significance

The results obtained in the present study emphasize the importance of heavy metal accumulation in industrially affected soils. Iron and chromium were found to be the most dominant heavy metals in the soils under investigation. Iron is a major constituent in soils due to its natural abundance. However, it's very high levels in the soils studied point to the possibility that its accumulation is not governed by natural factors alone. Chromium is generally linked to industrial wastes containing metals, metal treatment operations, pigments, and combustion residues.

Lead and zinc, too, showed an increase above the control level, which may be due to contamination from industrial sources, transportation activities, discarded

materials, or mixed waste sources. The increase in lead concentration at S3 may be due to a local source or mechanism, while the high zinc concentration at S1 may be due to different patterns of sources for different metals in the same industrial area.

The pattern of manganese contamination is moderate overall, although the distinct peak at S5 suggests that some areas of the study region are more prone to metal contamination than others. The repeated appearance of S5 across the various indices suggests that this location may warrant closer environmental scrutiny and may even be considered first in any future remediation strategy.

In conclusion, the results show that the reliance on the concentrations alone would not have given a complete representation of the severity and distribution of the pollution. The combined use of CF, Igeo, and PLI offered a complete interpretation of the pollution status and helped to identify which metals were the worst affected and which locations were the worst affected. This is a very useful tool in the assessment of industrial pollution in soils.

IV. CONCLUSION

In this study, the contamination of heavy metals in the soil of an industrially influenced area of Kerala, using measured values of concentration as well as selected pollution indices, is examined. The results show that all the metals under investigation are found to be higher than the background values, proving the effect of industrial influence on soil. Among all the metals, iron contamination is found to be extremely high at all the sampling points. Chromium, lead, zinc, and manganese have moderate to considerable contamination.

From all the sampling points, it can be concluded that sampling point S5 is the most polluted when all factors are taken into consideration. The results have shown that the use of pollution indices can be an effective means of determining the degree of contamination. The study recommends that the area be monitored regularly, while the causes of contamination are to be further investigated.

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